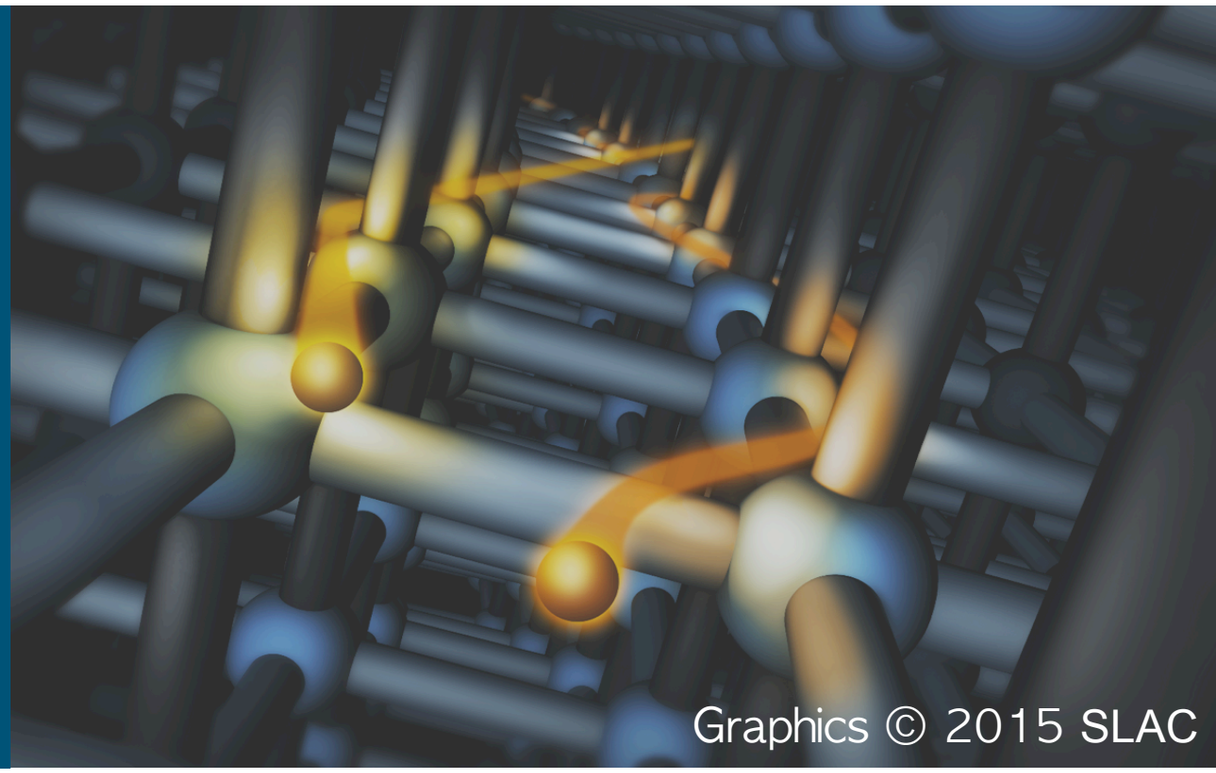
Channeling and VR Experiments at SLAC FACET and ESTB



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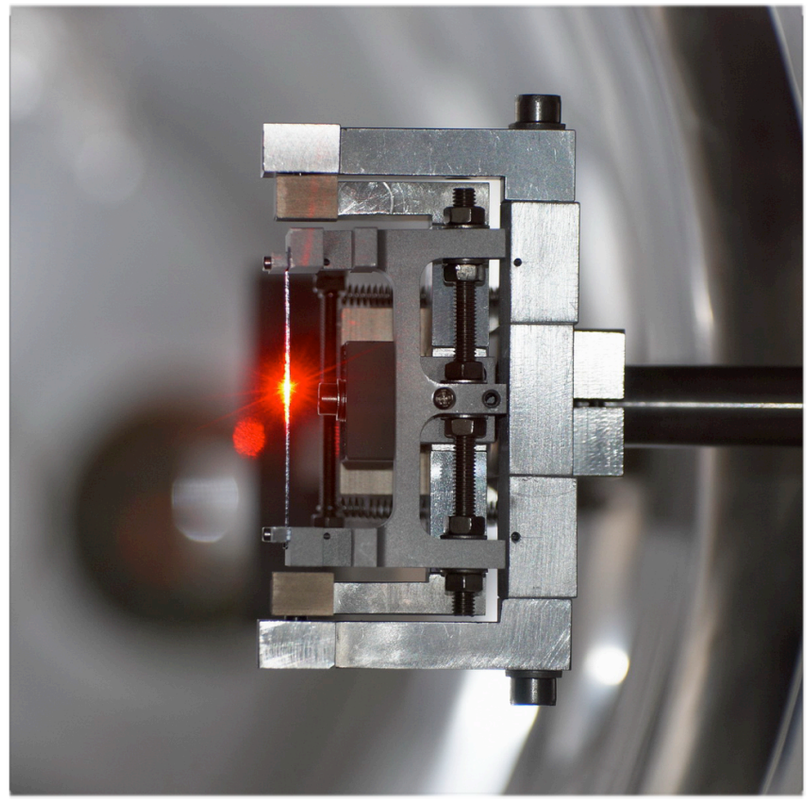
Motivation (deflection)

- Bent crystals can deflect high energy beams with small bending radii (O(0.1m)). At 30 GeV, ≈ 1000T B-field(!)
  - lots of proton data, little data for high-energy e^- or e^+
  - There is interest in crystal collimation for e^+ and e^-
    - Expected benefits in size and efficiency of collimation
    - Not enough data to actually design such a system
  - What channeling efficiency can one expect?
  - How does it scale with beam energy?
  - Can VR be used for beam collimation?

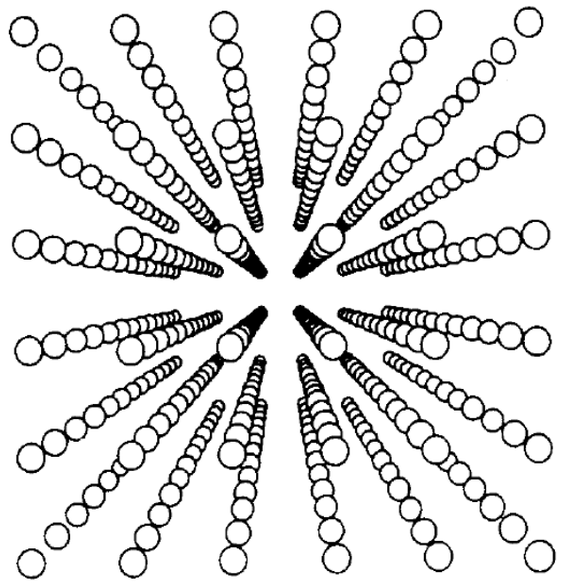


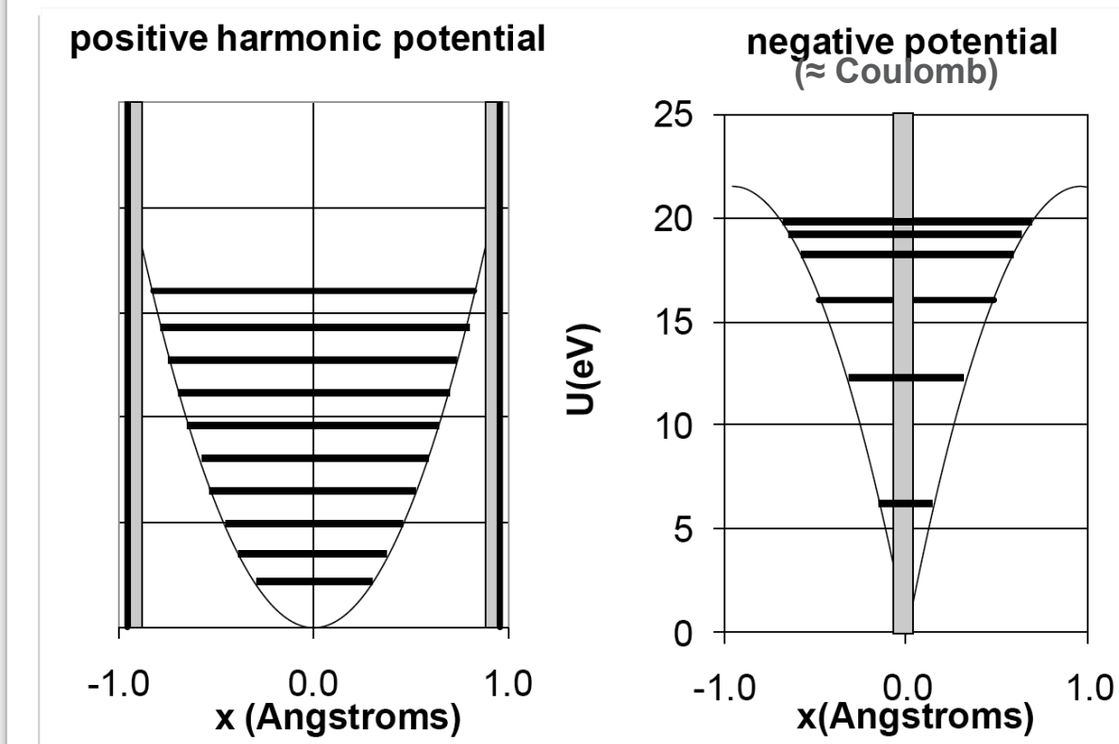
CERN SPS-UA9 collimator crystal

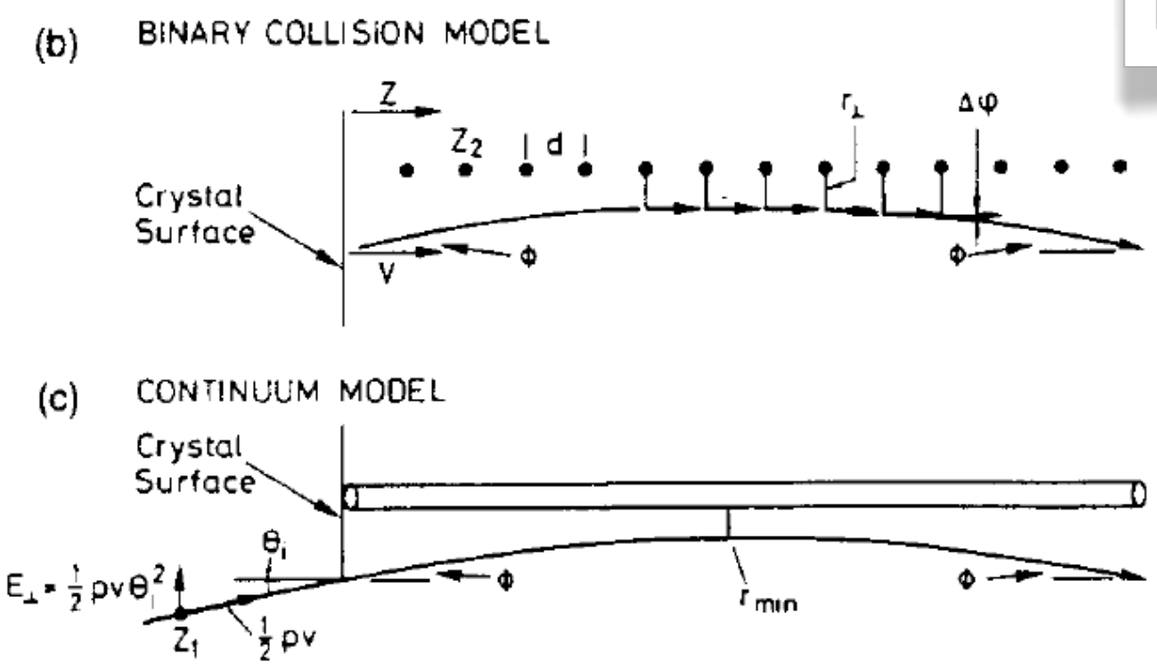
Motivation (radiation)

- There is interest in channeling radiation
  - Intense γ ray production, can we demonstrate narrow-band?
  - Use Crystal undulators with e^- ??
  - Can we make use of VR radiation?
- γ rays have applications in materials science and radiography techniques
  - penetrating γ rays can radiograph thick pieces.
  - crystal targets have been used with some success in γ sources for photo-nuclear reactions.
- Can crystal sources become competitive to Compton sources?

Channeling Potentials







Binary collision: deflection ∑ scatters

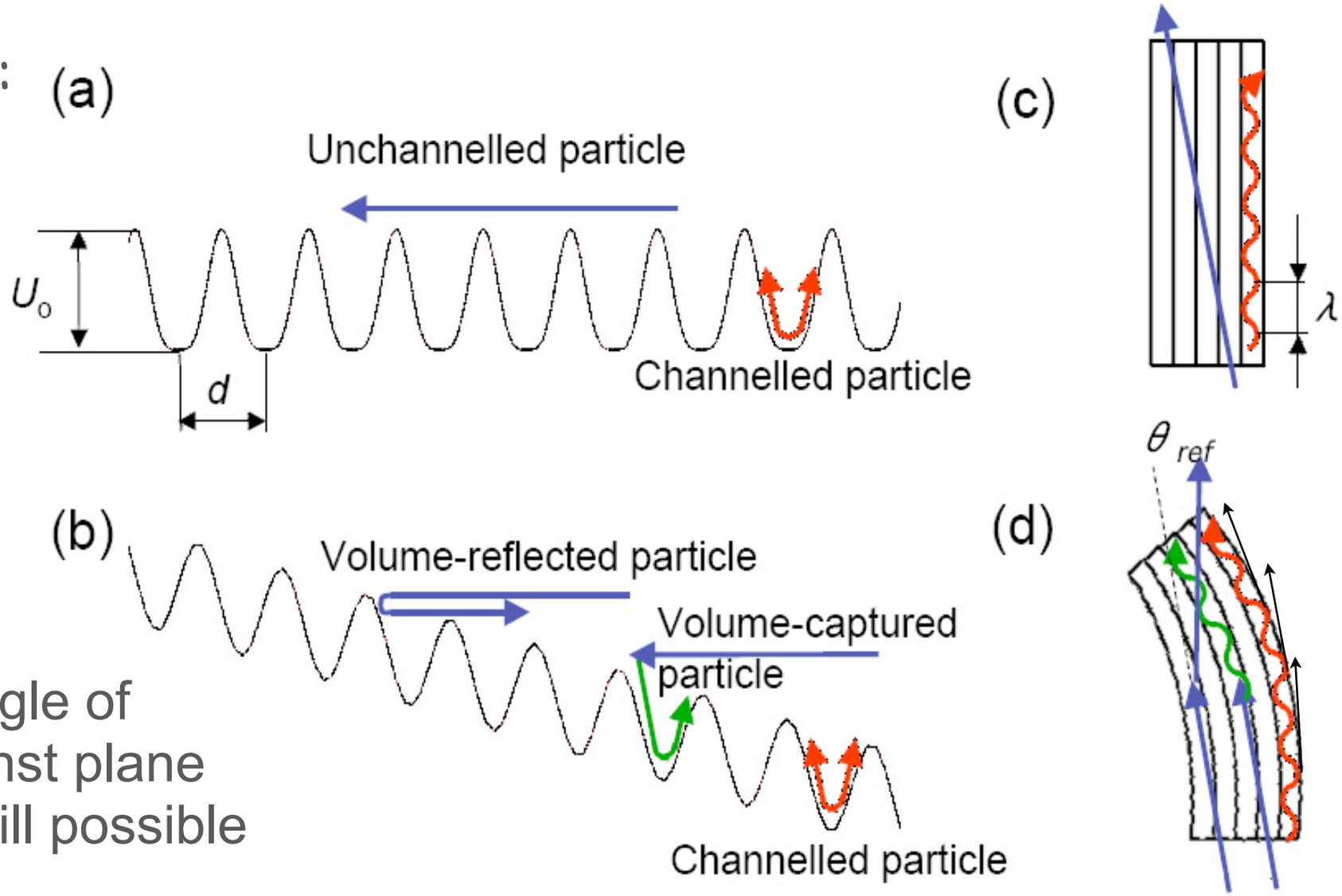
Continuum model: average potential

Particle-Beam–Crystal Interaction

(adapted from W. Scandale)

Possible processes:

- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection



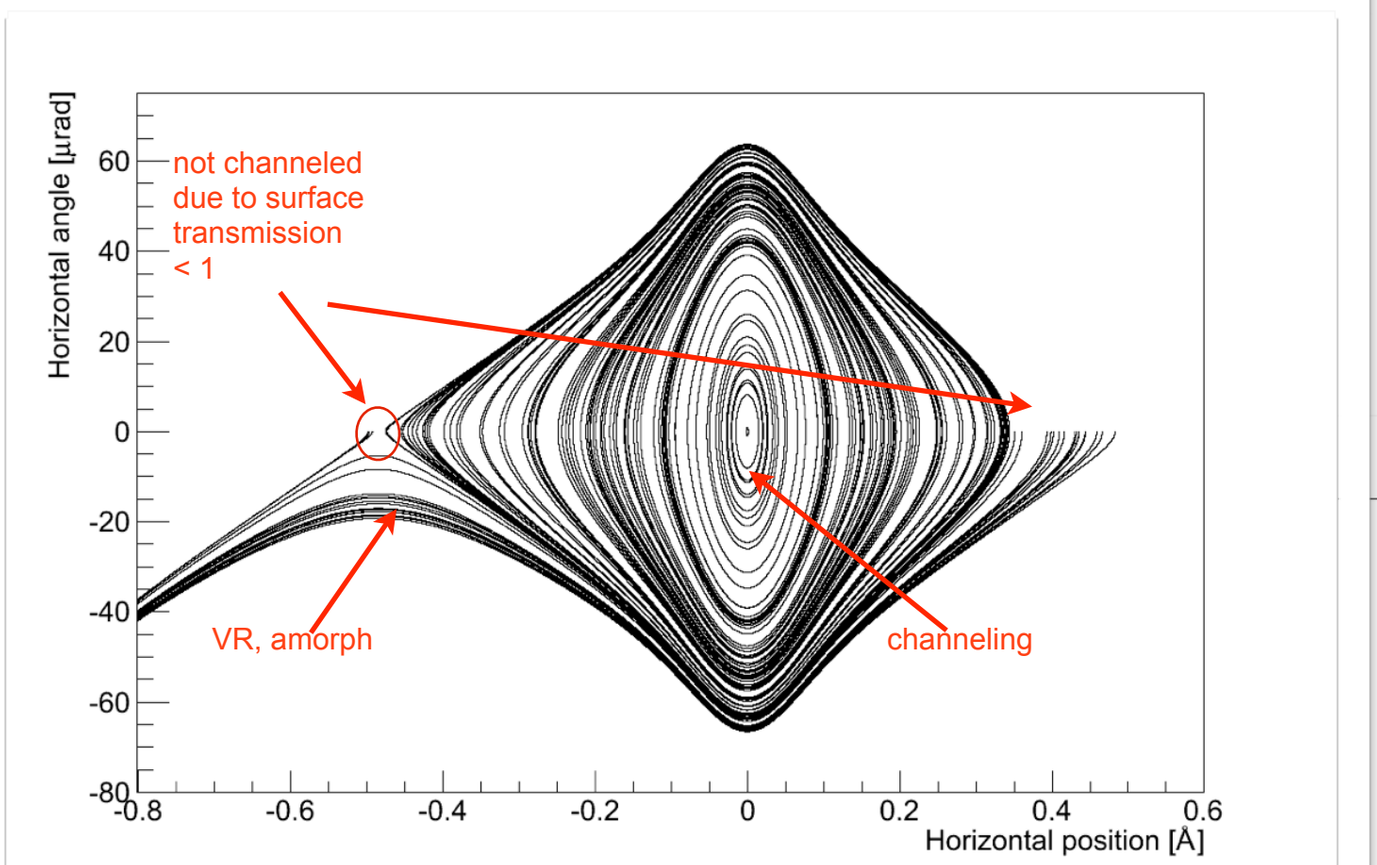
Critical angle: max. angle of incoming particle against plane where channeling is still possible

$\theta_{crit} = \sqrt{2U_0/E}$

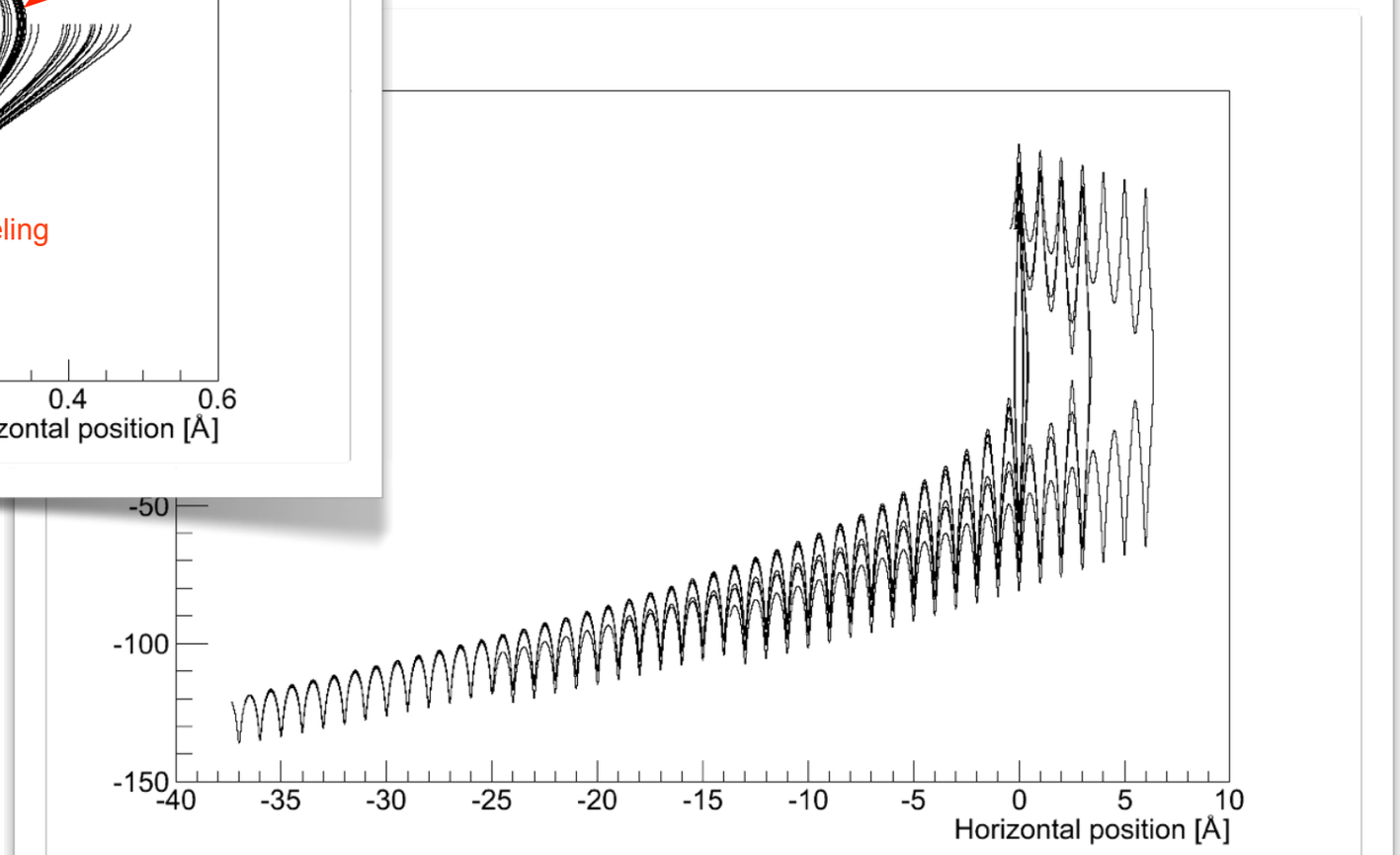
Dechanneling rate ∝ # in channel => ∝ exp(-s/L_d); L_d is called *dechanneling length*

Phase Space (bent crystal)

- Same topology as a (stationary or moving) rf bucket



(Plots by E. Bagli)

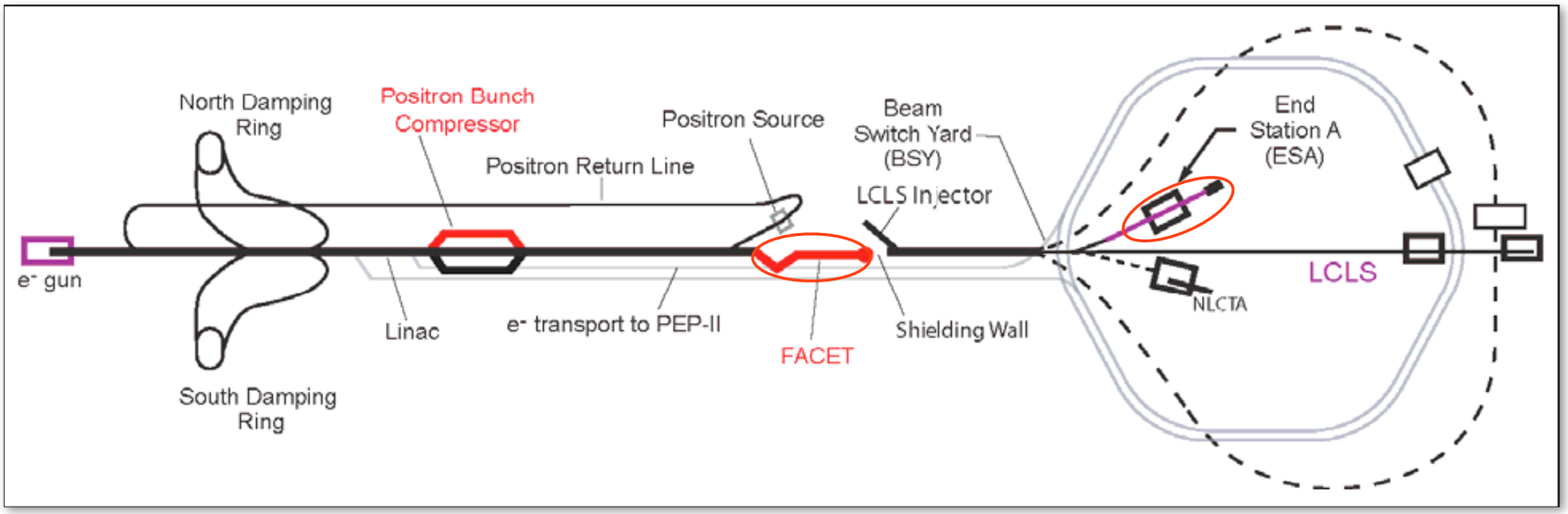


Channeling and VR Experiments at SLAC

- T513 (Wienands et al., ESTB, complete)
  - Channeling and Volume-Reflection Studies of High-Energy Electrons in Crystals
  - SLAC—U Ferrara—U Aarhus—Cal Poly
- E212 (U. Uggerhøj et al., FACET)
  - Radiation from GeV electrons in diamond – with intensities approaching the amplified radiation regime
  - U Aarhus—U Ferrara—SLAC—Cal Poly
- T523 (Wienands et al., ESTB)
  - γ -Ray Production Study with Electrons
  - SLAC—U Ferrara—U Aarhus—Cal Poly

FACET and the End Station A Test Beam (ESTB) 2010…2016

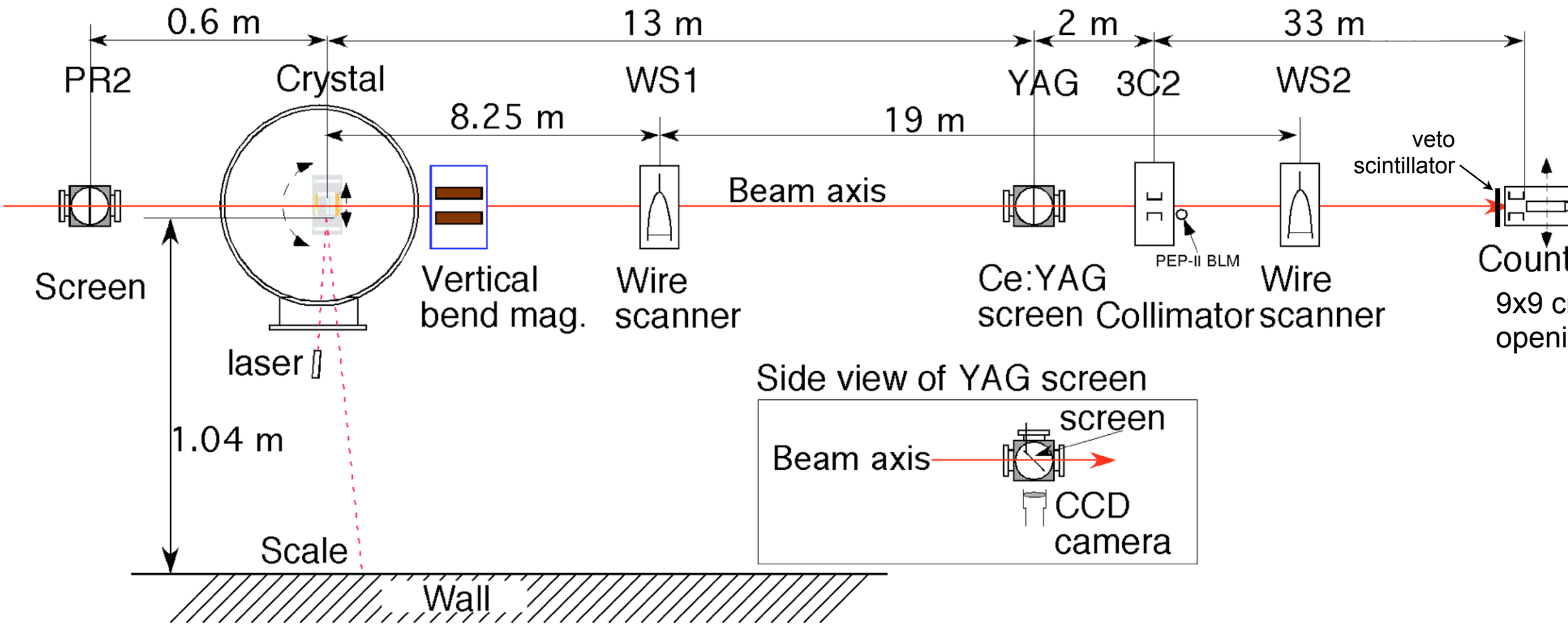
- ESTB: up to 15 GeV e^-, 5 Hz, ≤ 200 pC/pulse
  - "pulse stealing" from LCLS
- FACET: 20 GeV e^+ or e^-, 2 nC/pulse, 10 Hz, "20^3 μm^3"
- control of optics, momentum spread
  - both can provide relatively parallel beam (<10 μrad)
  - FACET has a e^- spectrometer downstream; ≈ 0.1% resolution



T513/T523 Setup at ESTB

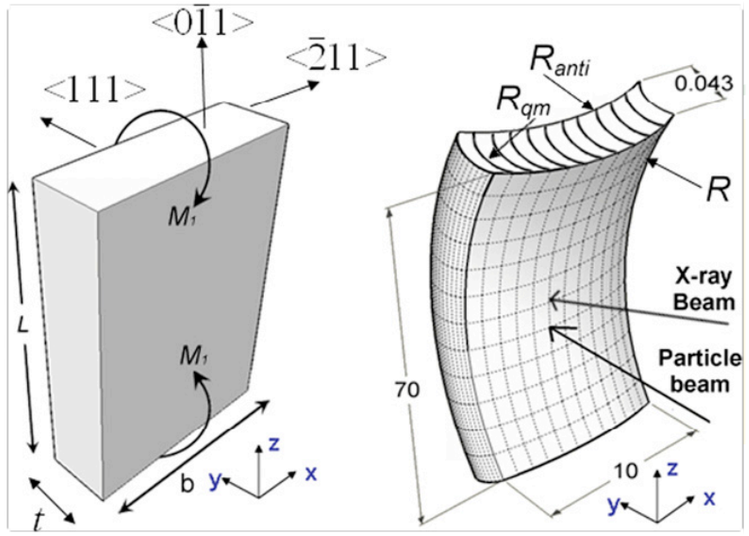
- E212 FACET Setup conceptually similar, but no γ counter

Top View, not to scale



A. Mazzolari

Main crystal features

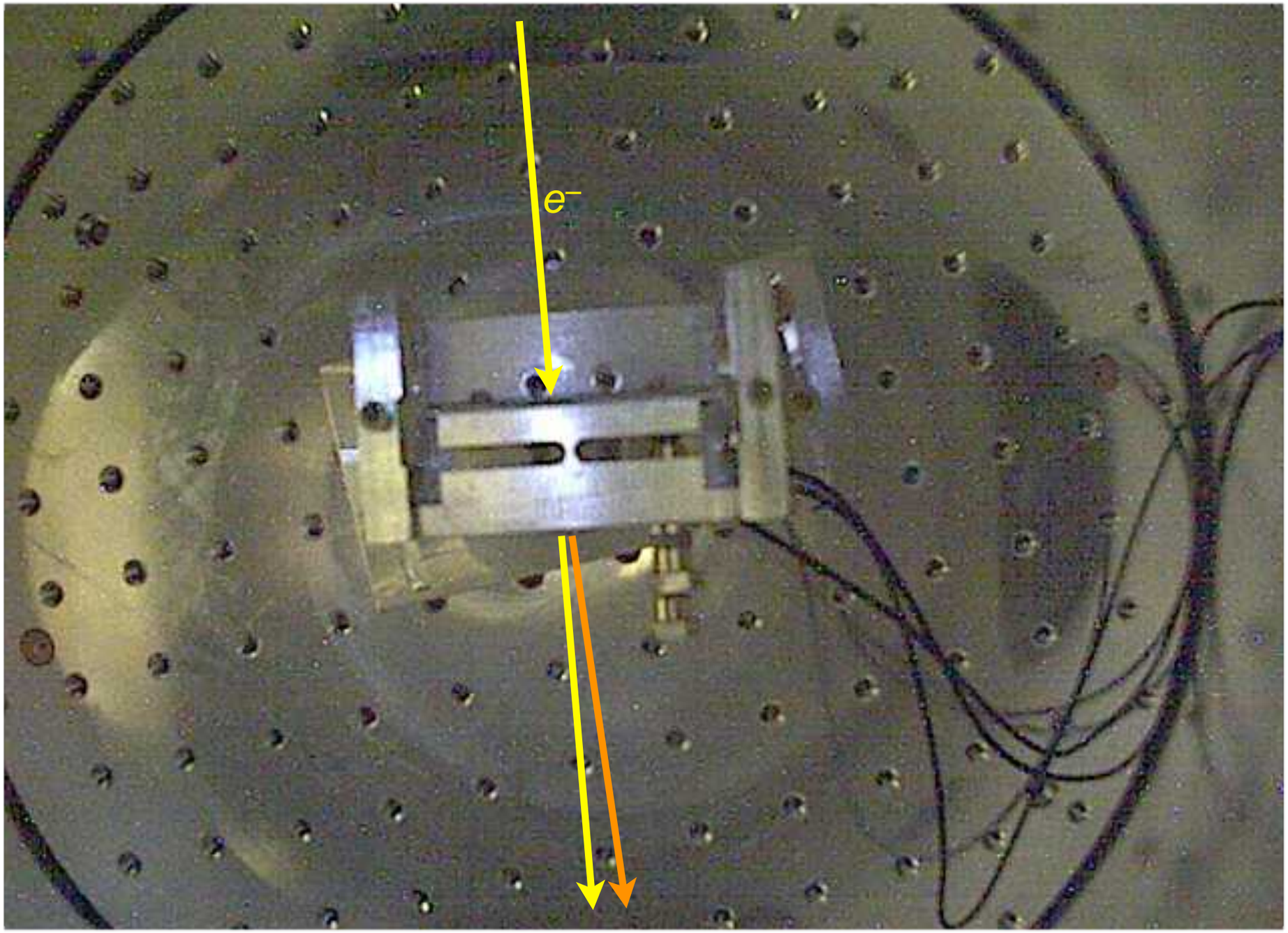


- **Crystal thickness 60±1 μm**
  Once the crystal will be back in Ferrara we will measure crystal thickness with accuracy of a few nm.

- **(111) bent planes (the best planes for channeling of negative particles).**

- **Bending angle 402±9 μrad (x-ray measured). If needed I can provide a value with lower uncertainty.**

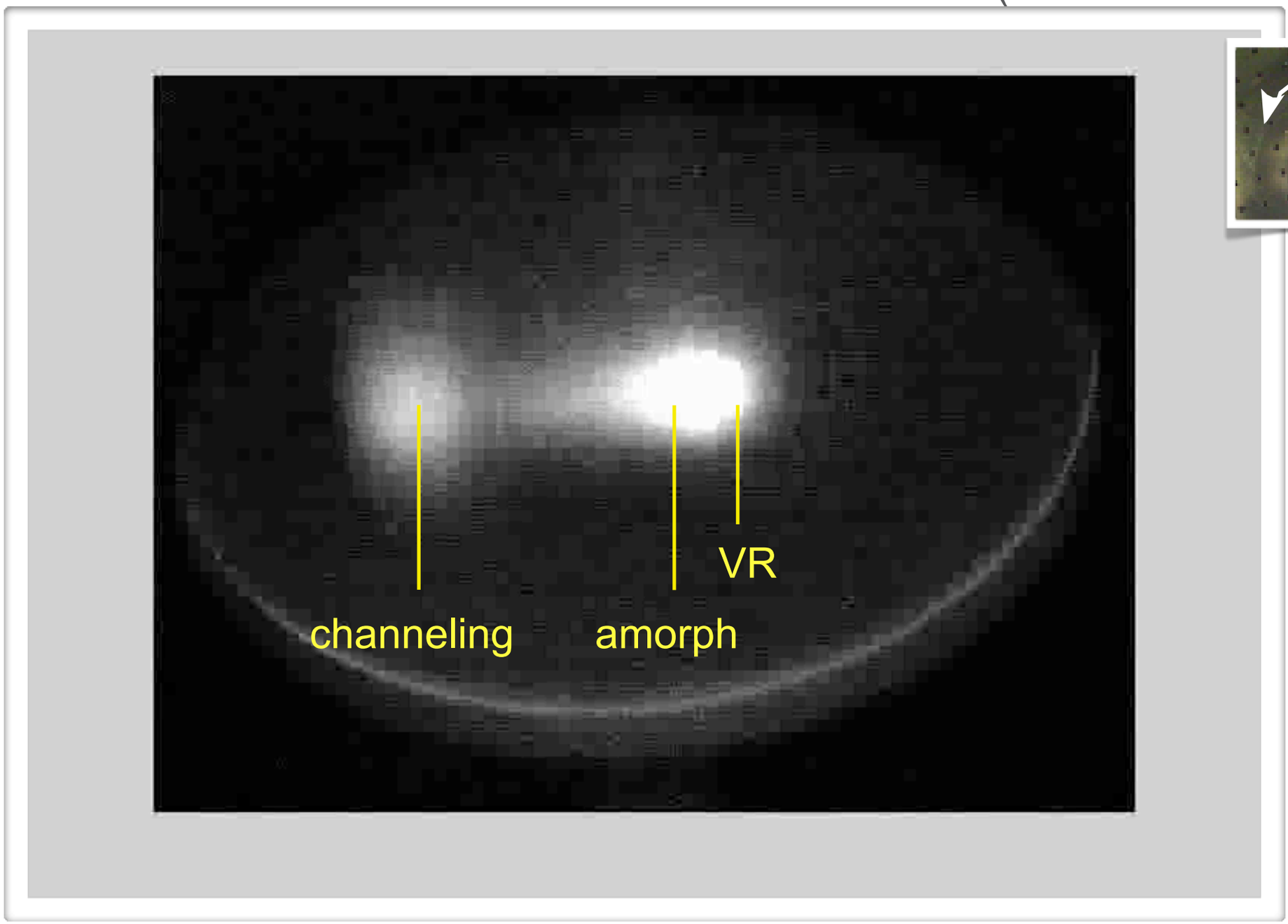
Crystal mounted in “Kraken” Chamber in ESA



First Demonstrated Deflection @ 4.2 GeV

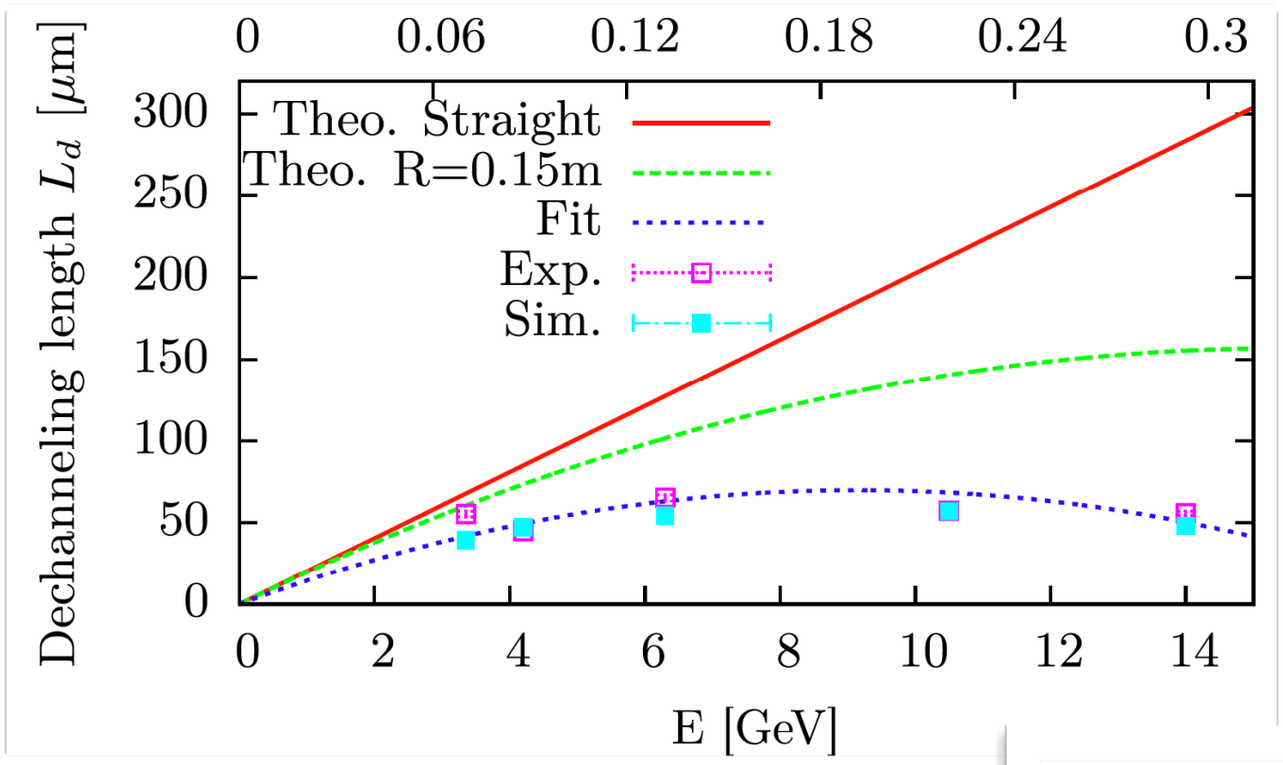
Wienands et al., Physical Review Letters **114,** 2015, 074801

(Movie credit: T. Wistisen)



https://www6.slac.stanford.edu/news/2015-02-25-slac-led-research-team-bends-highly-energetic-electron-beam-crystal.aspx

e^- Channeling and VR Parameters (T513)



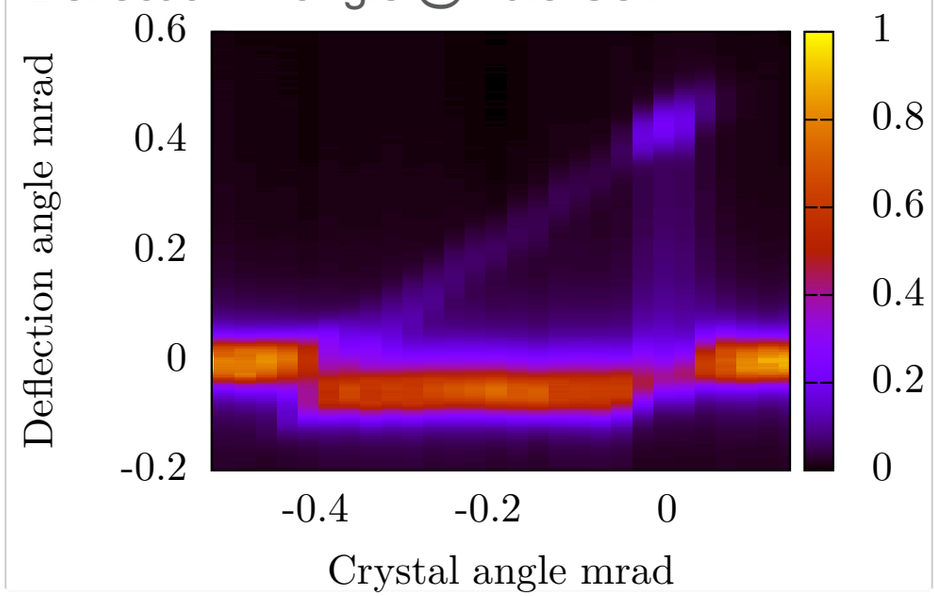
Ferrara Si(111)crystal,
60 µm, 400 µrad

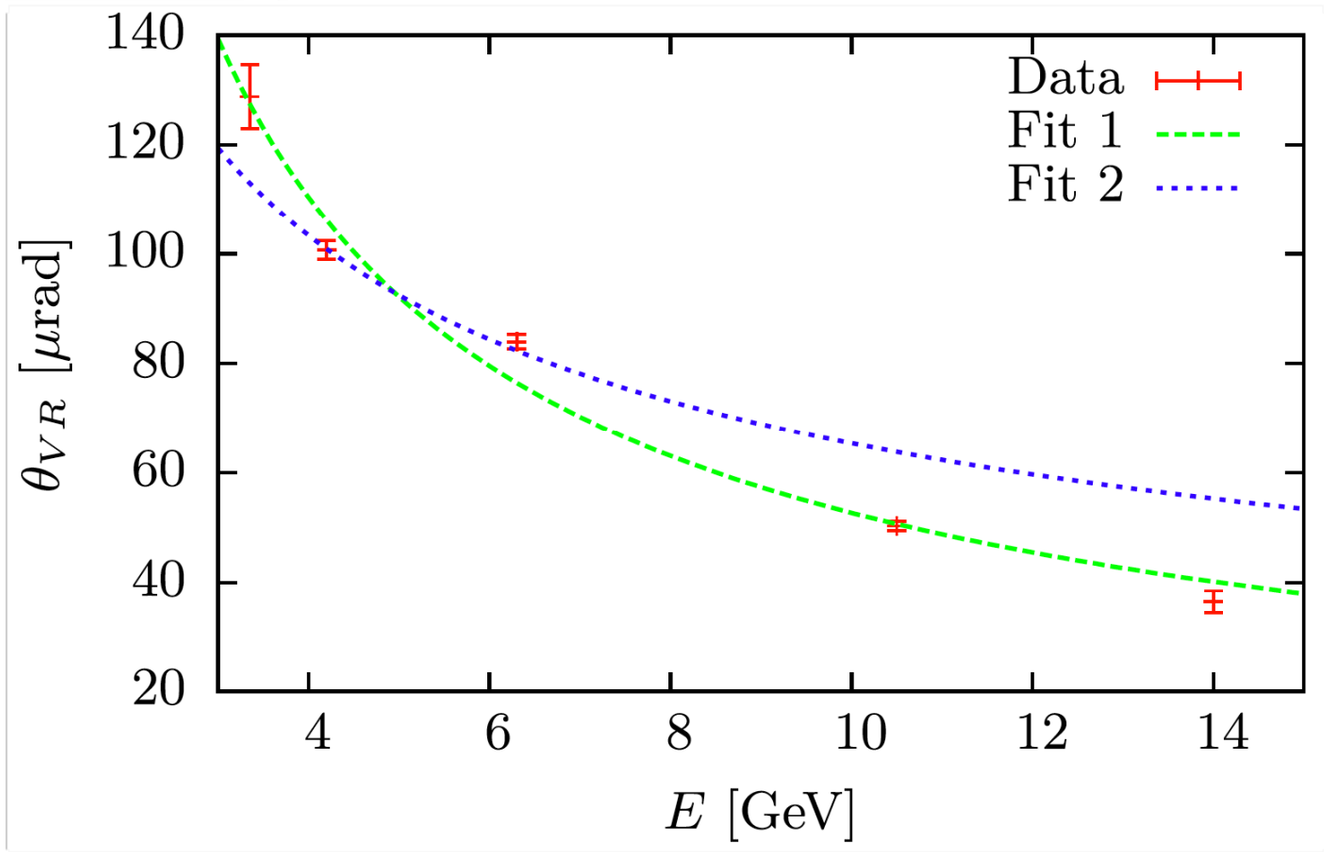
Channeling efficiency 18..24 %

Volume Reflection efficiency ≈ 95 %

T.N. Wistisen et al.,
Phys. Rev. ST-AB 19, 071001 (2016)

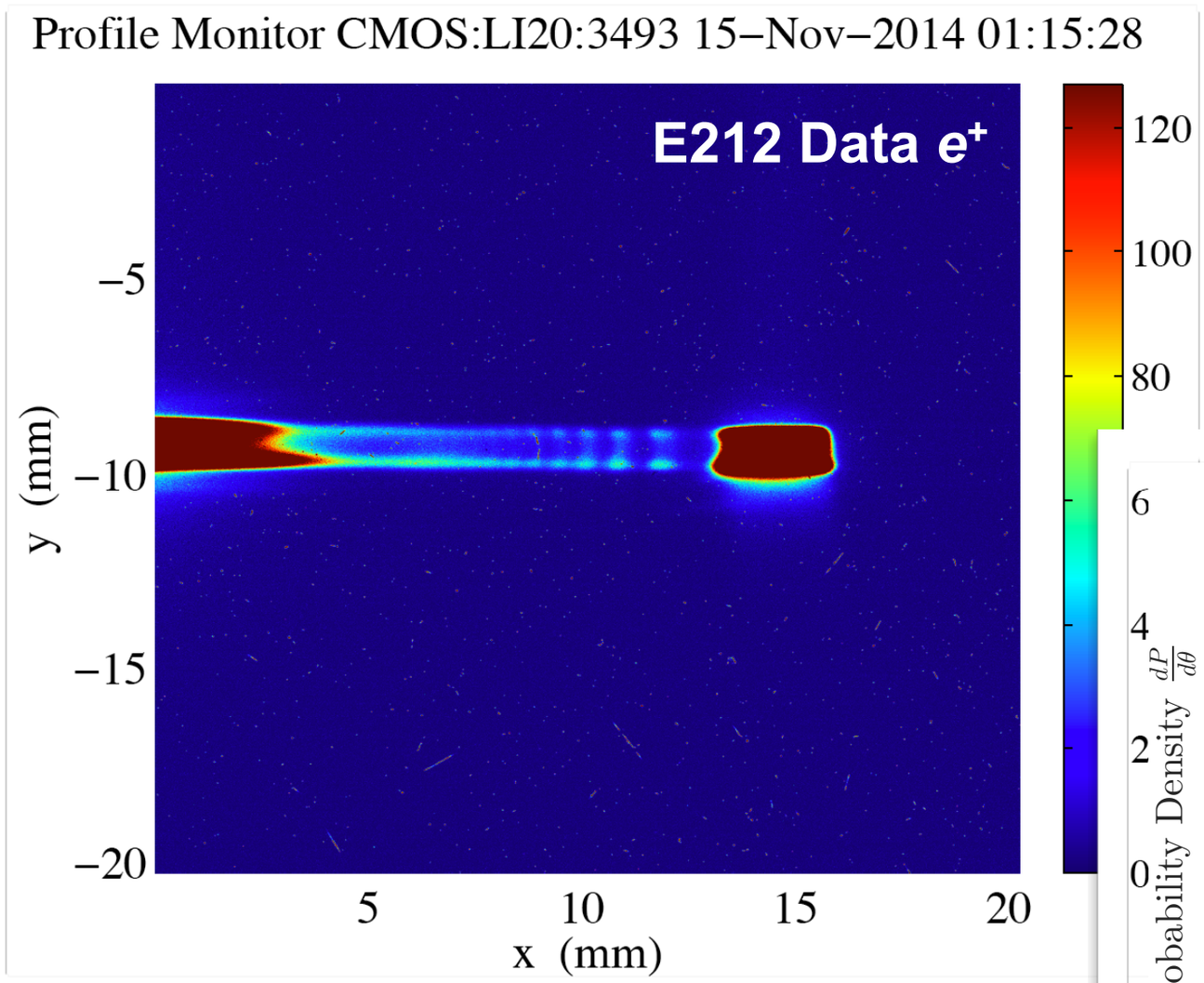
Deflection Triangle @ 10.5 GeV





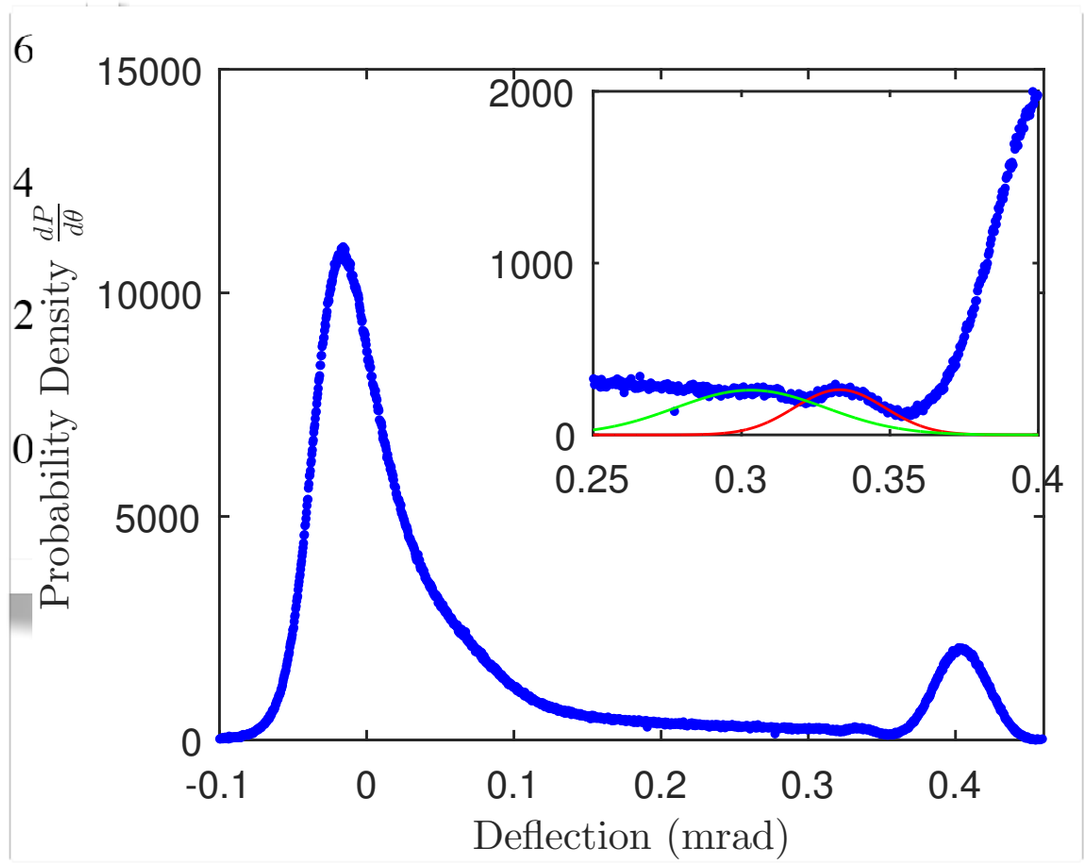
E212: First Channeling Data of 20 GeV e^+ in Bent Crystal

- Raw data



20.35 GeV e^+
10^{10} e^+/pulse

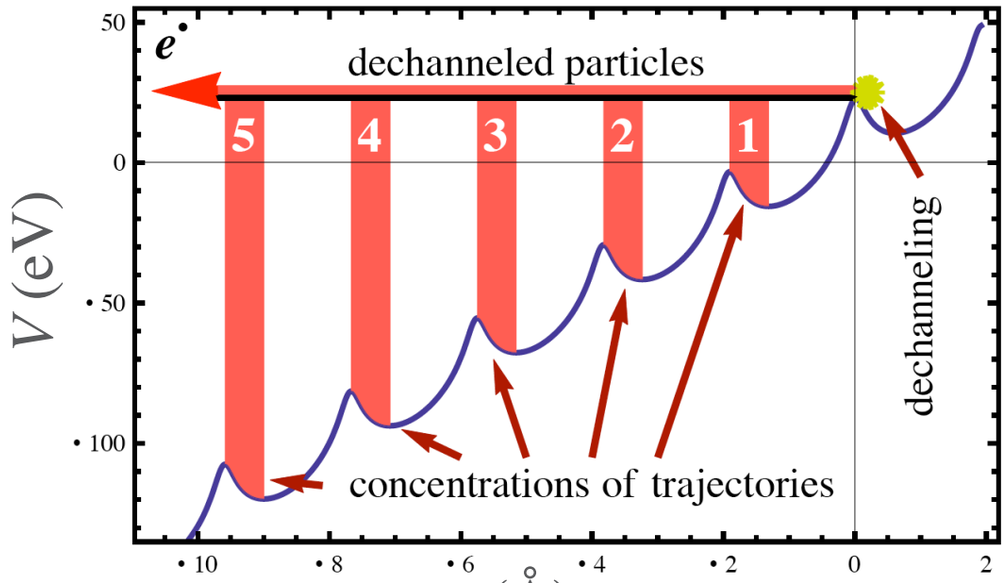
e^- data, 20.35 GeV, 10^{10} e^-/pulse

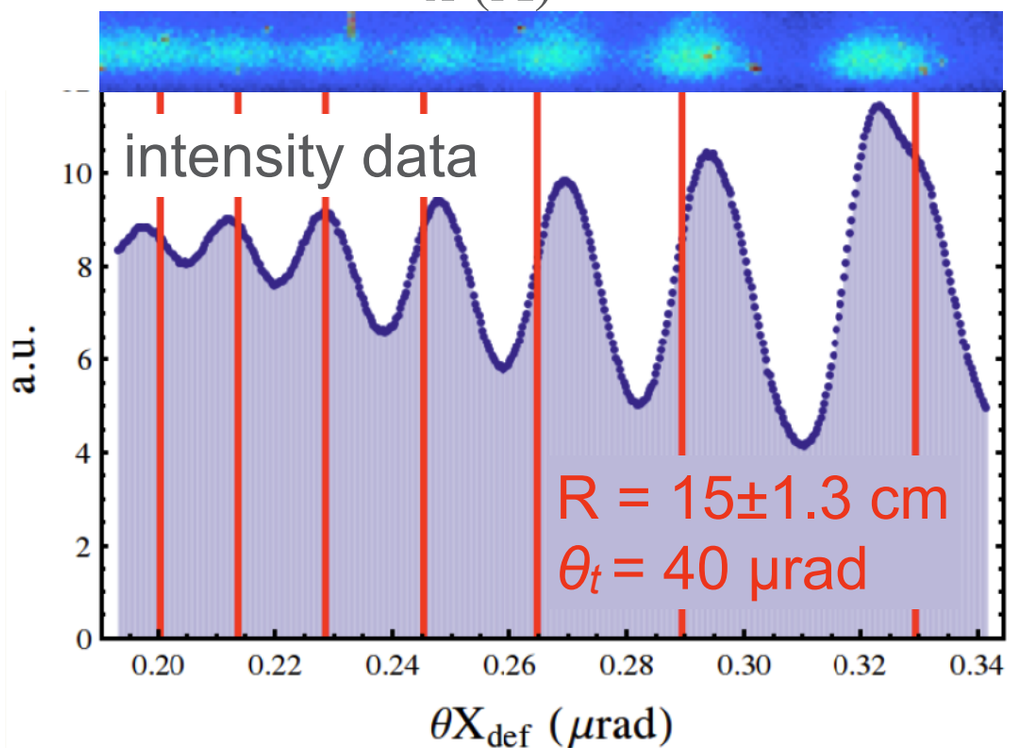


Analysis of the "Quasi-Channeling Oscillations"

A. Sytov et al., Eur. Phys. J. C (2016) **76**: 77

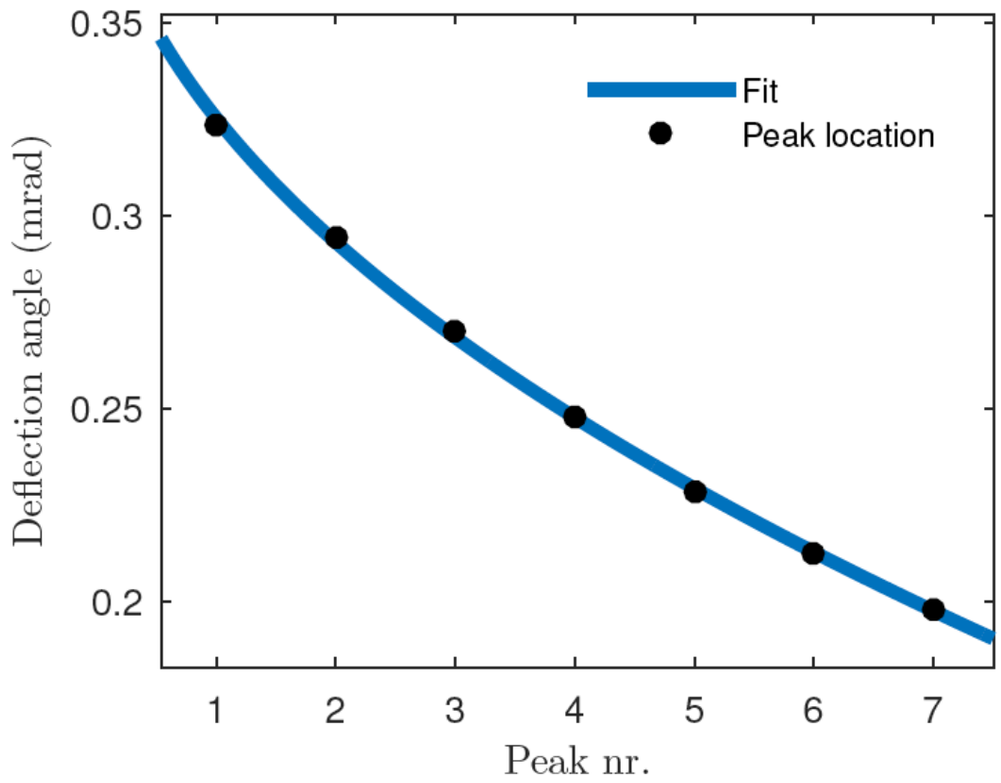
T.N. Wistisen et al., Phys. Rev. Lett. **119**, 024801 (2017)





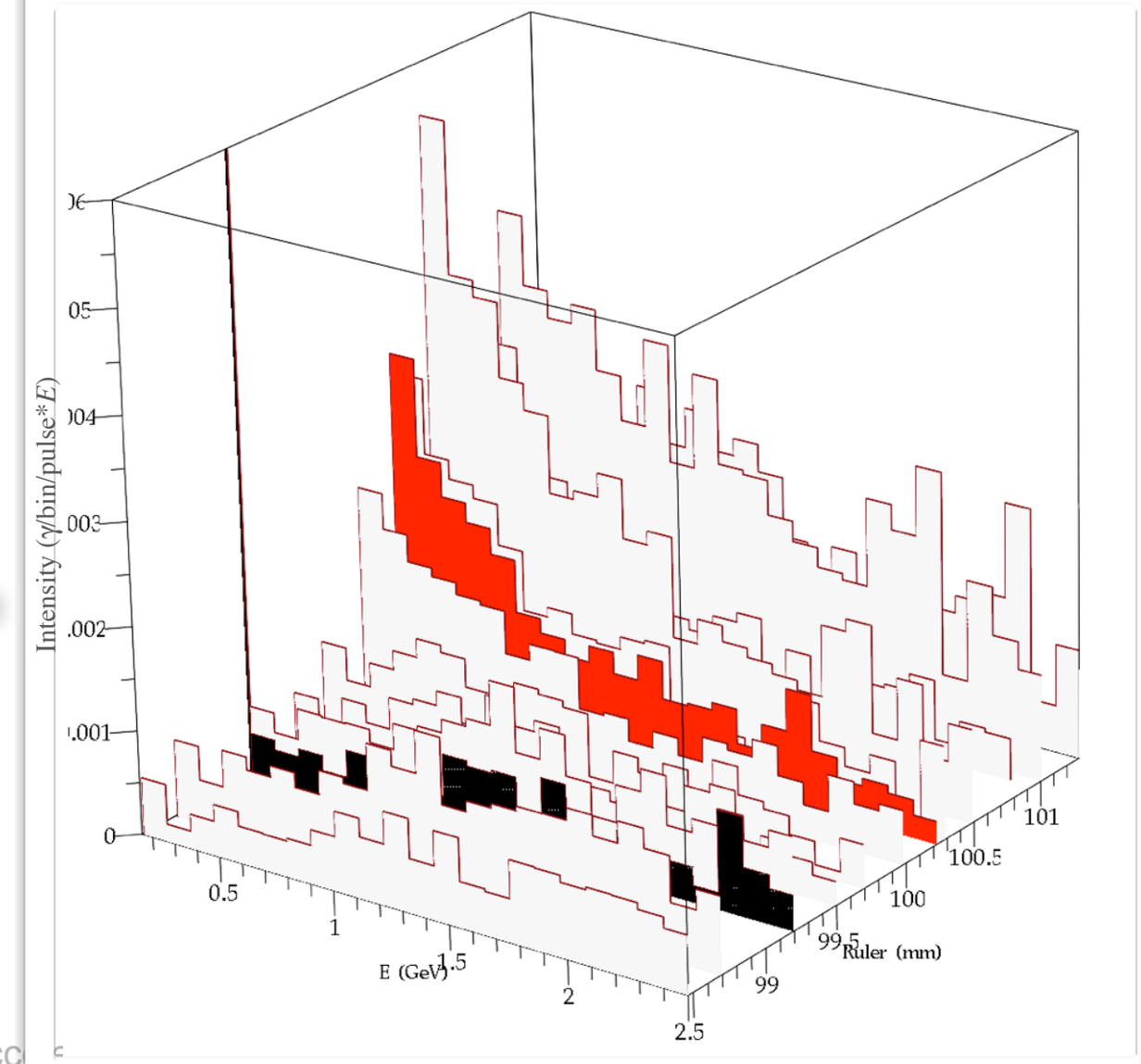
$$\theta_{def} = (\theta_b + \theta_t) - \sqrt{\frac{2d_0(n-1)}{R} + \frac{2d_s}{R}}$$

$\theta_b = 402 \pm 9\ \mu\text{rad}$, $R = 0.15$ m,
$d_s = 3.14$Å (known), $d_0 = 4\ d_s$



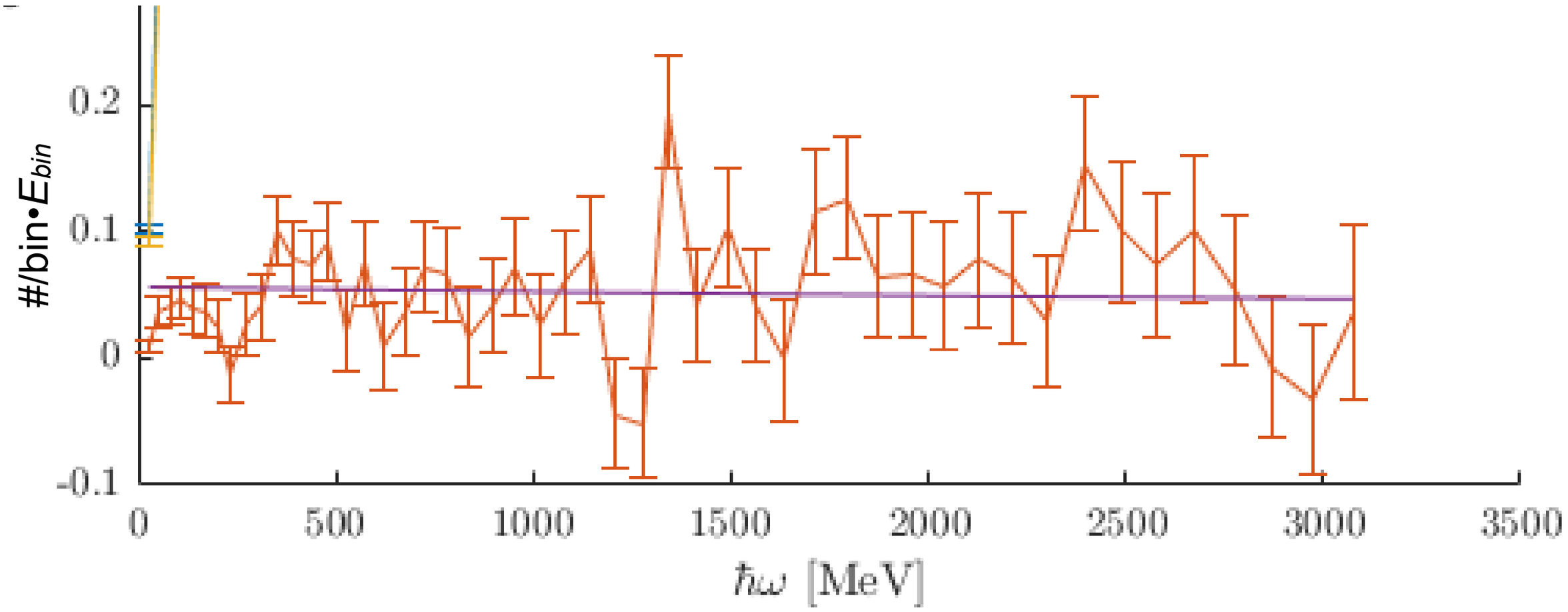
Radiation from Bent Crystal (T523, 2018)

- Secondary Beam producing ≈ 10 e^-/pulse
- Scintillating-Fiber (SciFi) calorimeter for γ detection ≤ 10 GeV
  - ≈ 10% energy resolution
- The electron spectrum is used to set beam intensity and calibrate the SciFi detector.
- 12.6 GeV beam energy
- We were able to take data along the whole deflection triangle.
- Raw spectra *vs* crystal angle



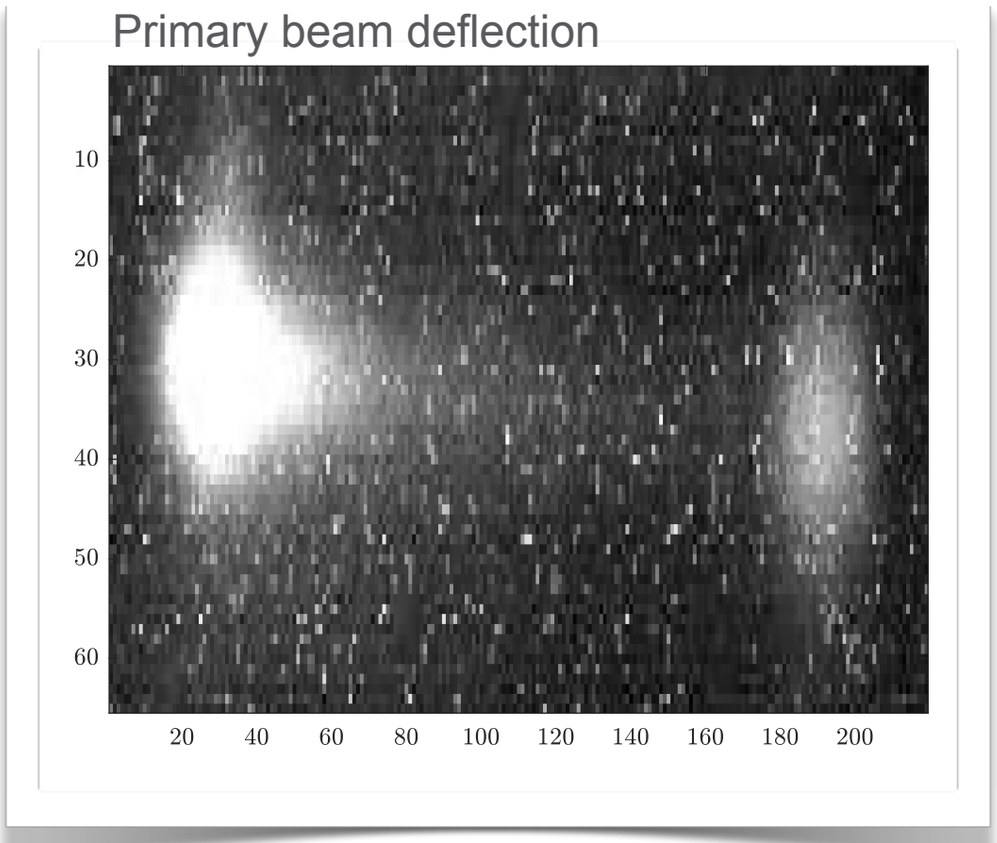
“Far Amorph” Spectrum

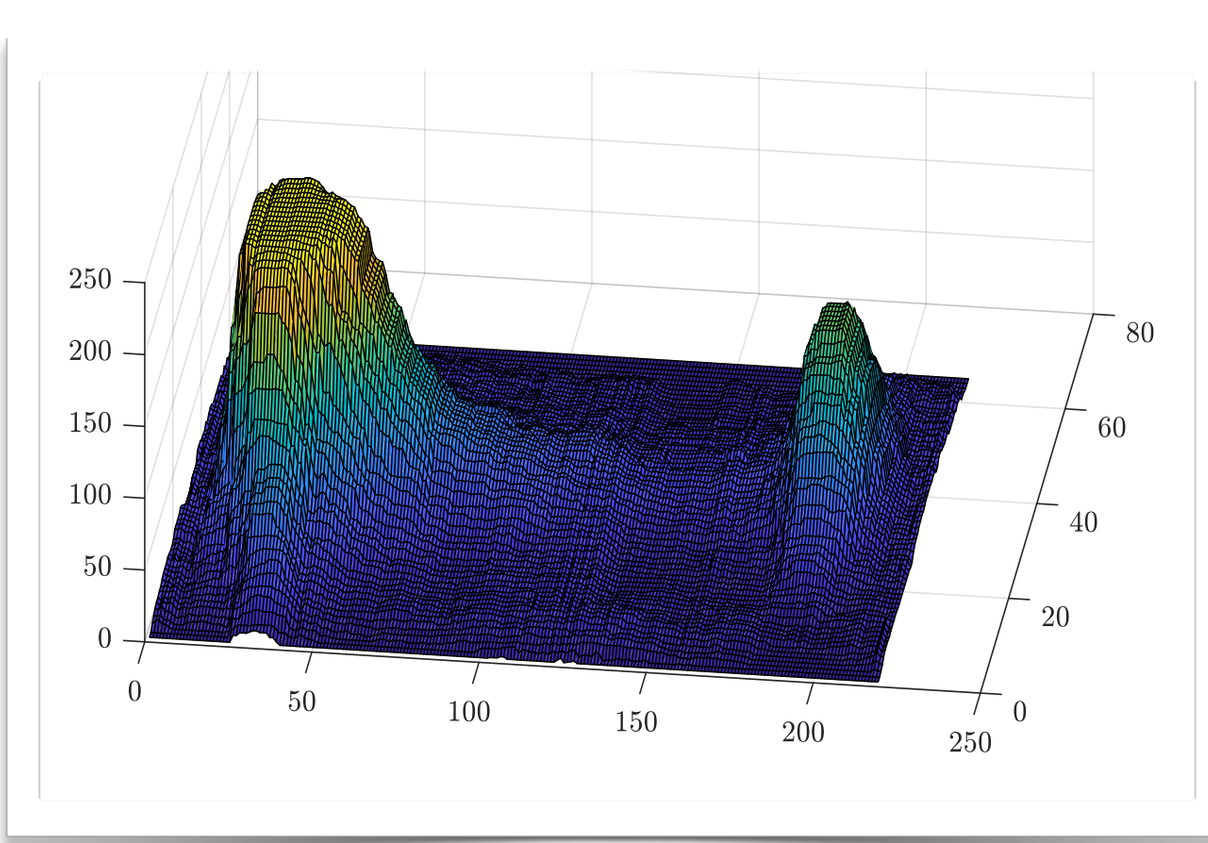
- Crystal angle far away (≥ 5 mrad) from channeling beam-line background subtracted
  - should be Bethe-Heitler (bremsstrahlung), flat in this presentation.
  - This is used to calibrate the intensity

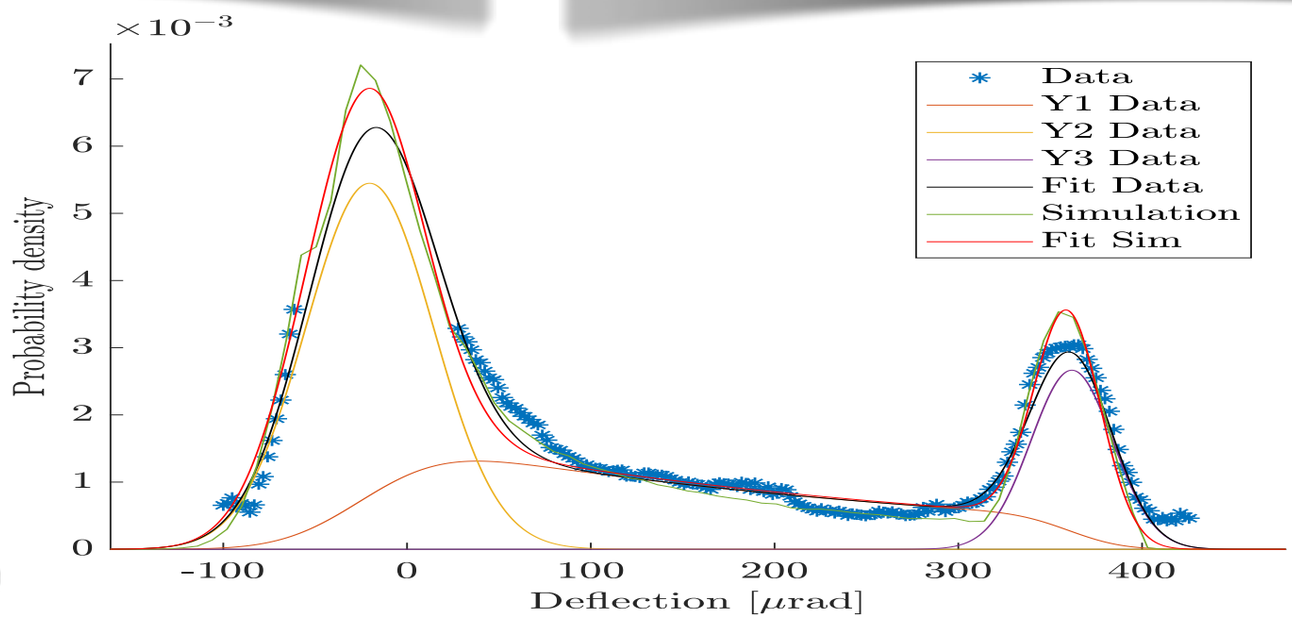


Deflection Calculations

- The code describes our exp. deflection with good accuracy
  - data right in line with our published T513 results







Radiation Model (C. Nielsen, to be published)

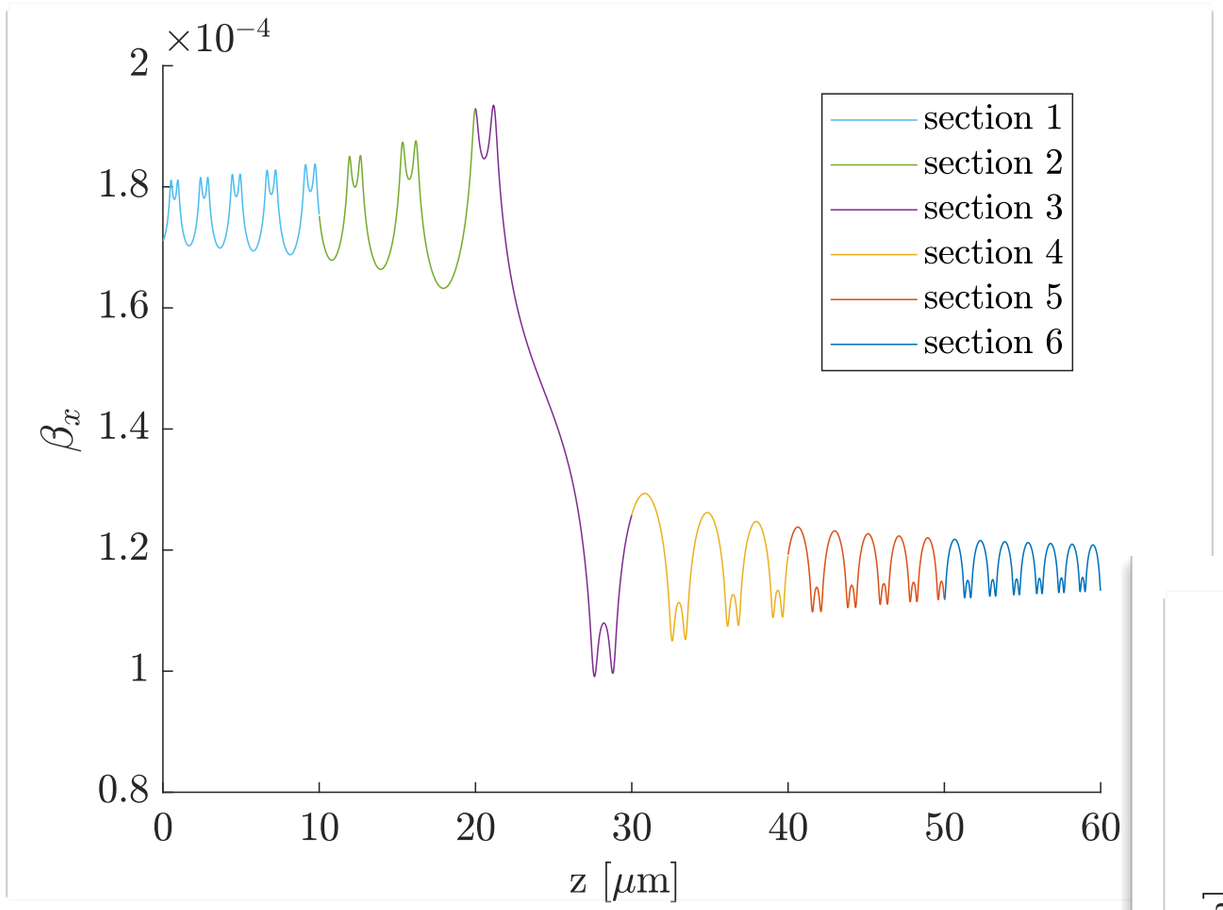
- Liénard-Wiechert spectrum (classical):

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{4\pi^2}\left|\int_{-\infty}^{\infty} \mathbf{f}(t,\mathbf{n})e^{i\omega(t-\mathbf{n}\cdot\mathbf{x}(t))}dt\right|^2,$$

$$\mathbf{f}(t,\mathbf{n}) = \frac{\mathbf{n}\times(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^2}, \qquad \boldsymbol{\beta} = \frac{v}{c}, \quad \dot{\beta} = \frac{dv}{dt}\frac{1}{c}$$

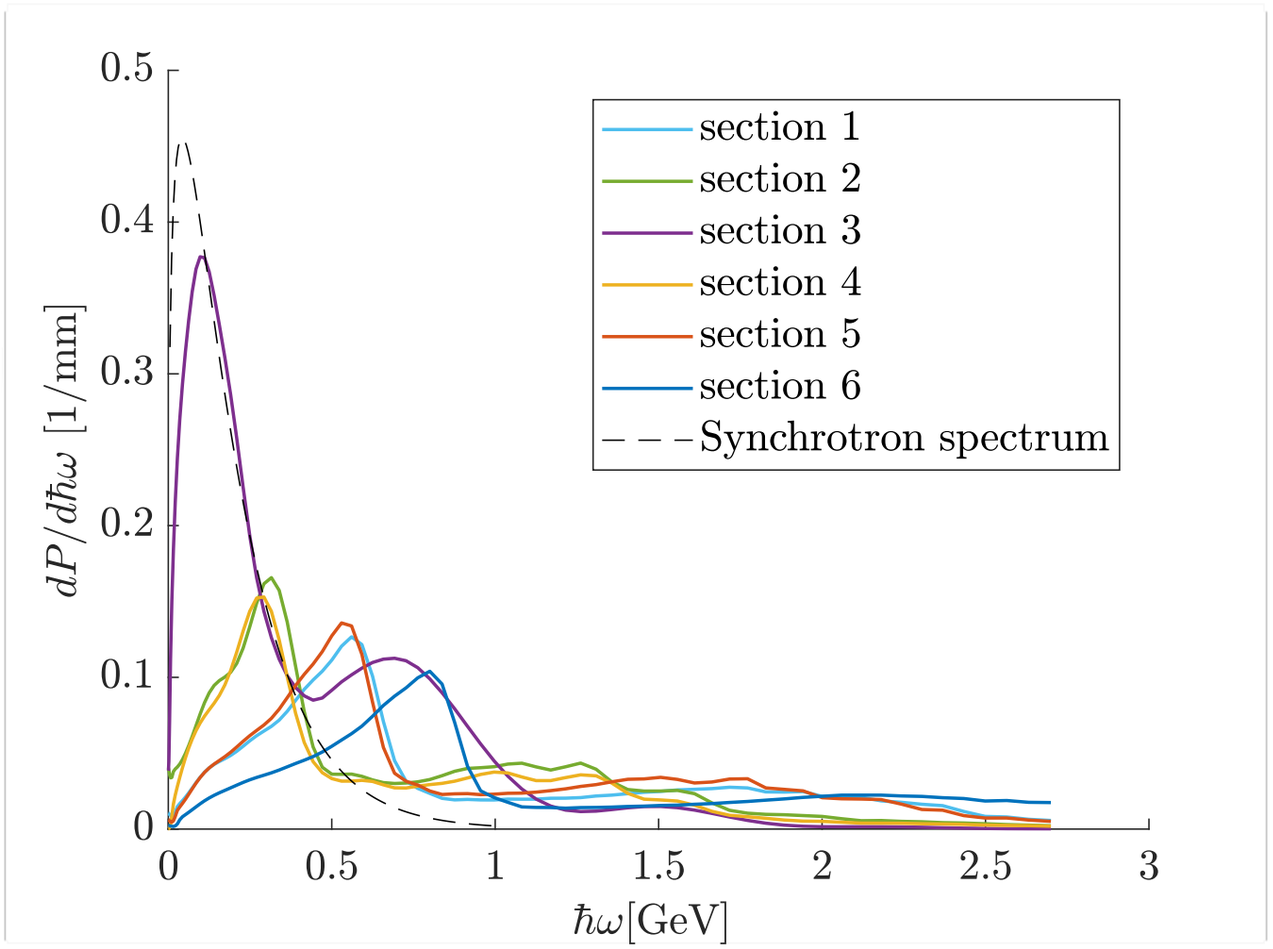
- solve the equation of motion in the crystal potential numerically using Doyle-Turner potential
- Then solve the radiation integral along this trajectory.
  - including photon recoil (quantum effect) and spin
  - single-photon emission.
- run on GPUs for speed.

Volume Reflection



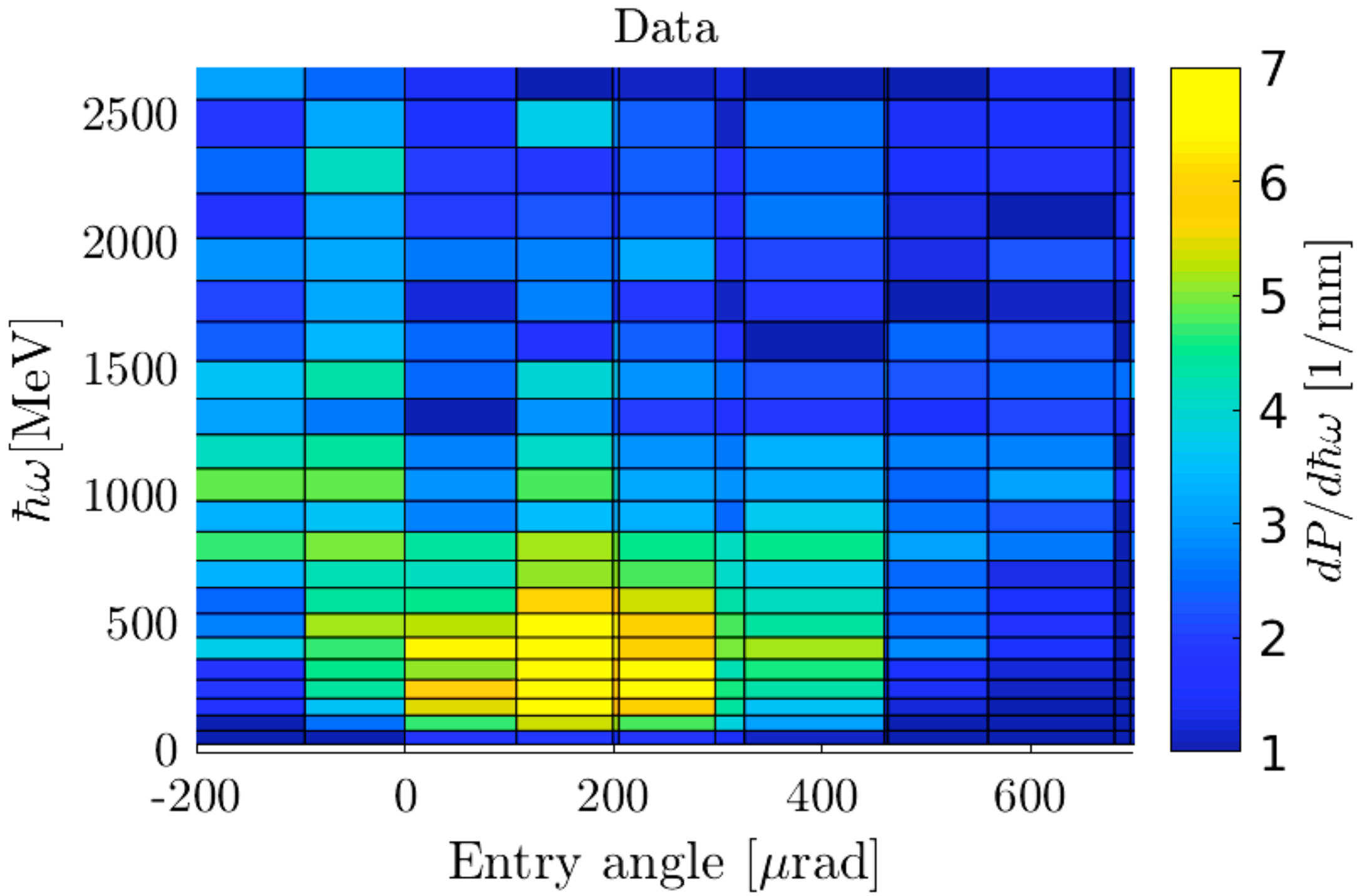
<—— transverse momentum *vs* z

Spectrum ——>



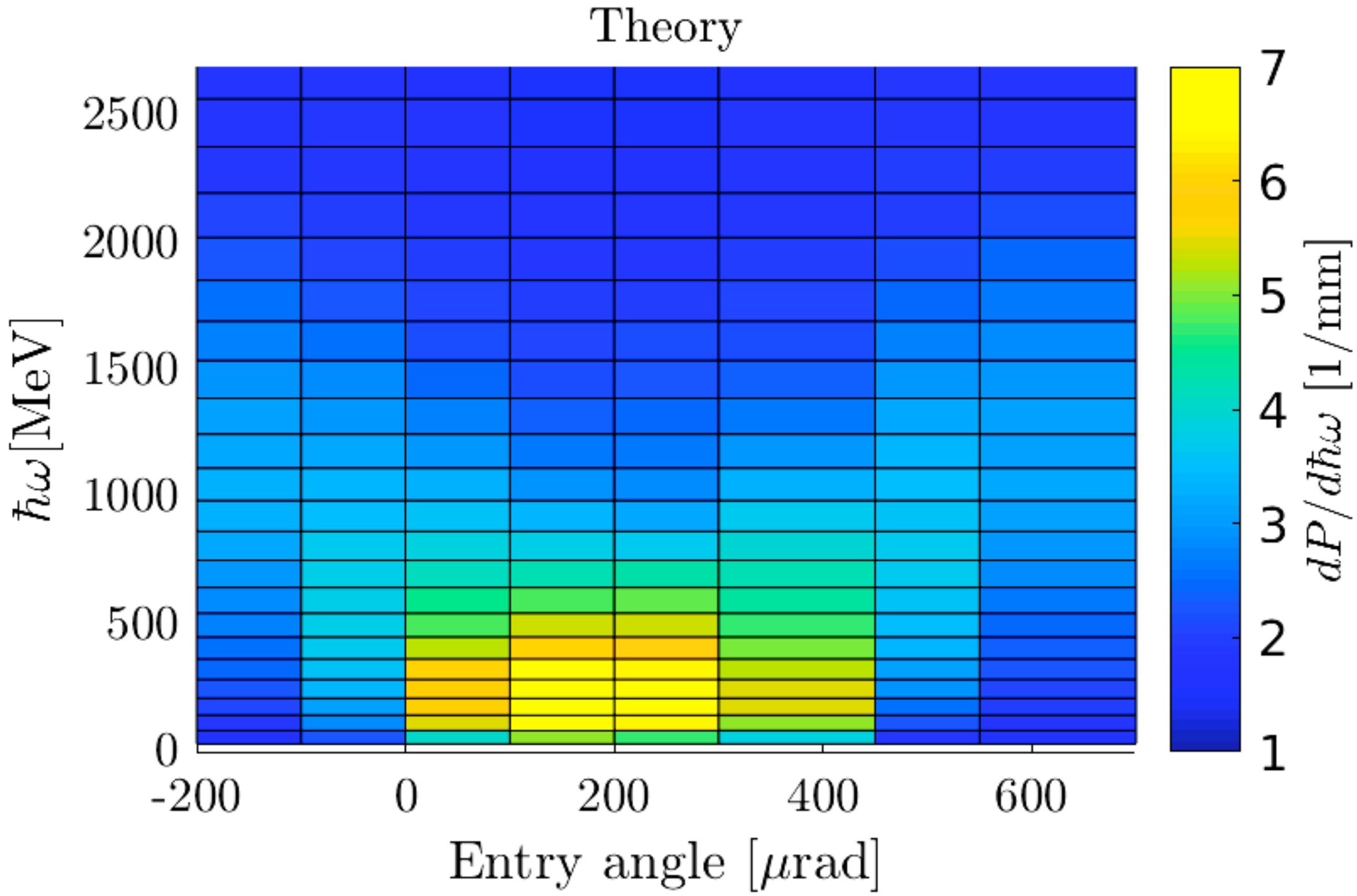
Spectrum-Angle Correlation (12.6 GeV)

Background-subtracted spectra normalized to linac pulses



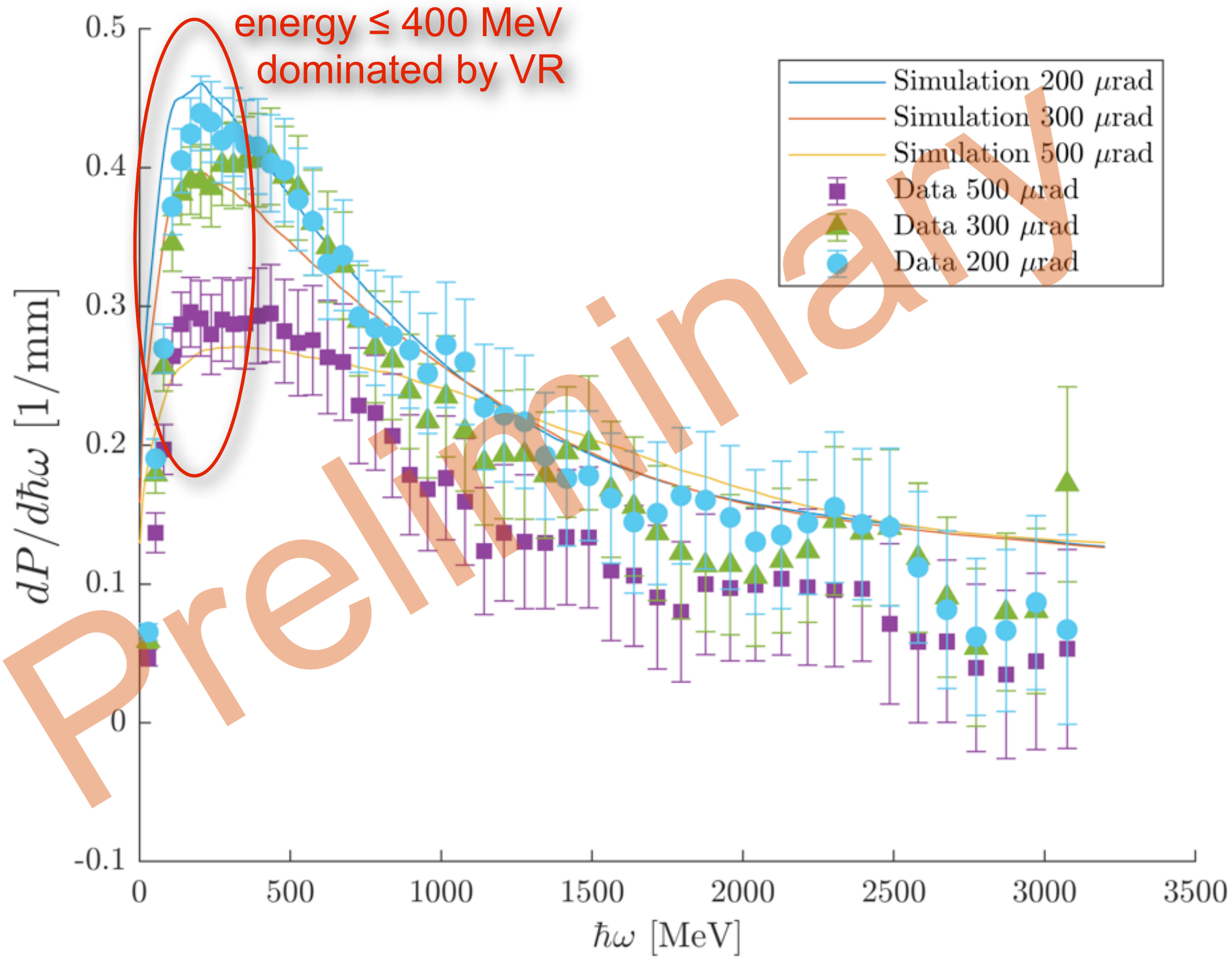
Spectrum-Angle Correlation (12.6 GeV)

Model spectra folded with 75 μr incoming beam divergence
Binning comparable to exp. data



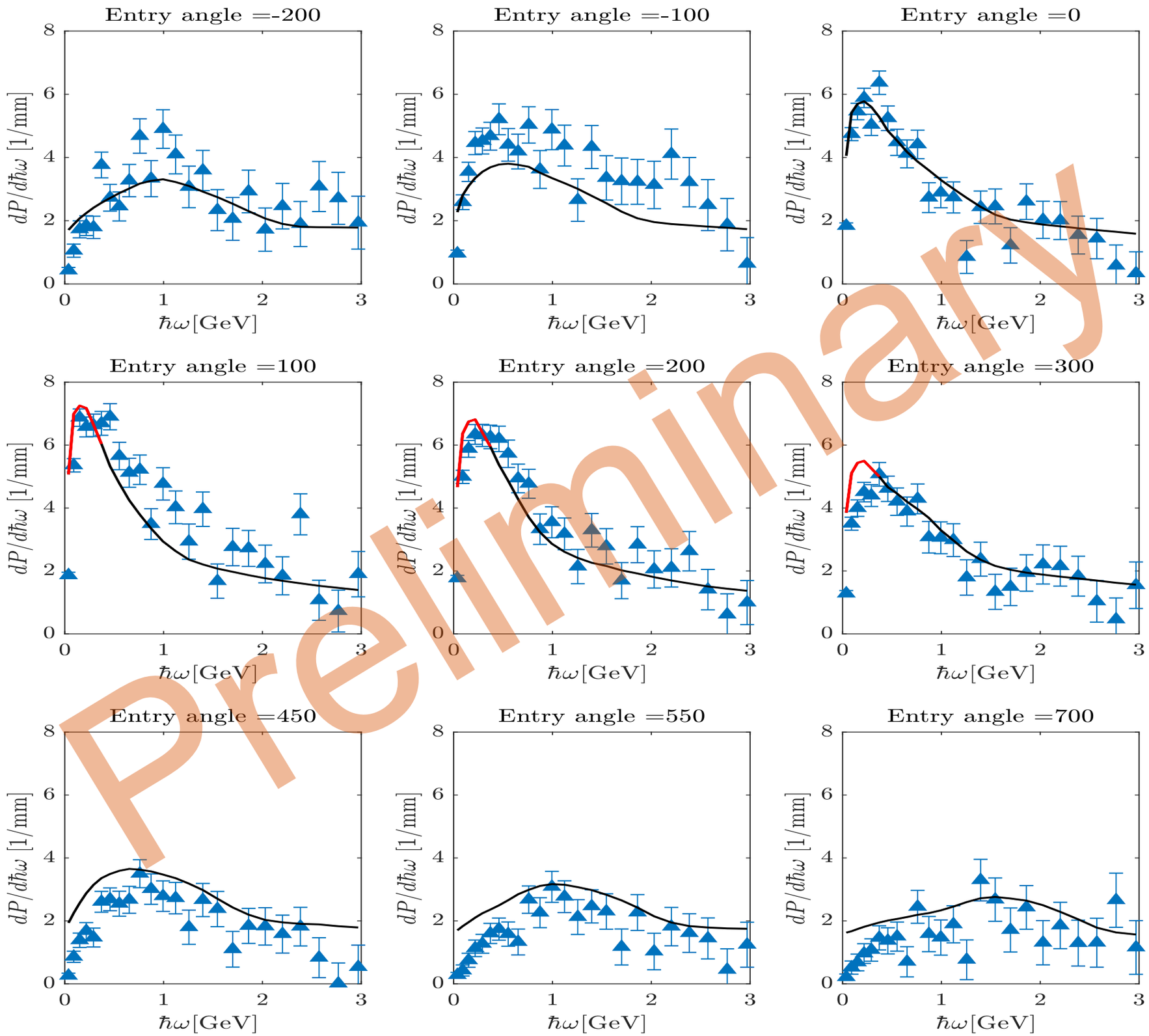
Measured Spectra and Model

- The far amorph (B-H) spectra are used to calibrate the intensity
  - ≈ 8 times B-H at low *E*



Spectra *vs* Crystal Angle

Red line indicates VR-dominant radiation



Summary

- The FACET and ESTB experiments now comprise a large fraction of the body of electron-channeling and VR data available in the world in the $\mathcal{O}(10)$ GeV energy range.
- First systematic measurements of electron channeling
- First detection of “quasi-channeling oscillations” with positrons.
  - They have also been seen, albeit weaker, with electrons.
- Recently first radiation experiment with bent crystal
  - energy spectra along the whole deflection triangle.
  - consistent with VR-radiation dominance at low energy
    - significant CBR contribution at higher energy
  - significant enhancement over B-H (≈ 8-fold near 200 MeV)

Outlook

- Understanding & modeling at GeV energies is on relatively firm ground
  - Study of channeling & radiation effects in CNTs should be feasible at SLAC FACET-II or ESTB

- Can we measure the influence of laser-driven fields on the particles?
  - predecessor to actual acceleration
  - γ radiation as probe of electron-field interaction?

Acknowledgments

- SLAC Test Facilities staff (C. Hast, K. Jobe, C. Clarke, M. Dunning) have been extremely supportive and instrumental in the success of the experiments.

- Janice Nelson, Tonee Smith and SLAC Accelerator Operations did yeoman's work setting up our beams and diagnosing issues when things looked weird.